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Direct CP violation at LHCb

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Abstract

During 2011, LHCb has collected an integrated luminosity of 1.0 fb^{-1} giving rise to a large variety of measurements. Among these, measurements of direct CP violation in B decays play a central role. Three different analyses are presented: the first evidence of CP violation in the B^0_s system and the observation of CP violation in the B^0 system, using $B^0 \to K\pi$ and $B^0_s \to \pi K$ decay channels; the evidence of CP violation in $B^\pm \to DK^\pm$ decays with the first observation of the suppressed ADS mode; and a preliminary result showing the evidence of CP asymmetry in charmless three-body charged B decays.

Keywords: LHCb, flavour physics, CP violation, beauty hadrons

1. Charmless two-body decays

The study of charmless two-body decays is of fundamental importance since they are potentially sensitive to new physics beyond the Standard Model. Charmless two-body decays have been extensively studied at the B factories [1, 2] and at the Tevatron [3] where CP violation has been well established in the $B^0 \to K^+\pi^-$ decay channel while for the B^0_s system, no evidence of CP violation has been found.

The measurements of the direct CP violating asymmetries in $B^0 \to K^+\pi^-$ and $B_s \to K^-\pi^+$ have been performed using data collected with the LHCb detector corresponding to an integrated luminosity of 0.35 fb^{-1} [4].

The direct CP asymmetry in the $B^0_{(s)}$ decay rate to the final state $f_{(s)}$ with $f = K^+\pi^-$ and $f_s = K^-\pi^+$ is defined as:

$$A_{\mathrm{CP}} = \Phi[\Gamma(\bar{B}^0_{(s)} \to \bar{f}_{(s)}), \Gamma(B^0_{(s)} \to f_{(s)})], \tag{1}$$

where $\Phi[X, Y] = (X - Y)/(X + Y)$ and $\bar{f}_{(s)}$ is the charge-conjugate state of $f_{(s)}$.

1.1. Selection Procedure

The online selection is based on a hadronic hardware trigger that selects high transverse energy clusters in the calorimeters and on a dedicated two-body software selection imposing requirements on the quality of the reconstructed tracks, their transverse momenta and their impact parameters; the distance of closest approach of the decay products of the B meson candidate, its transverse momentum, its impact parameter and the decay time in its rest frame. Two different sets of offline criteria have been optimized to maximise the sensitivity to the $A_{\mathrm{CP}}(B^0 \to K\pi)$ and to the $A_{\mathrm{CP}}(B^0_s \to K\pi)$ measurements. For the B^0_s decay a tighter selection is needed since the decay rate and the production rate are lower with respect to the B^0. The two selection criteria sets can be found in [4].

The selected candidates are reconstructed under the same pion mass hypothesis and then subdivided into different final states using the Particle Identification information (PID) provided by two RICH detectors. The PID information is a crucial aspect of the analysis. In order to estimate the background from other two-body B decays, a PID calibration procedure has been performed. The PID efficiency and the mis-ID rate have been estimated from data using a calibration sample of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ for pions and kaons and $\Lambda \to p\pi^-$ for protons. The PID information is not used in these calibration samples since the final state can be correctly reconstructed using only kinematic criteria. Since the

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PID performance is momentum dependent, the distributions have been reweighted according to the momentum distribution of the B decay products. The typical PID efficiency for the $A_{\rm CP}(B^0 \to K\pi)$ selection is ~69% and ~38% for the $A_{\rm CP}(B_s^0 \to K\pi)$.

An unbinned maximum likelihood fit has been performed to the selected events (Figure 1). From the mass fits the signal yields and the "raw" asymmetries have been determined.

1.2. Instrumental and production asymmetries

Corrections to the raw asymmetries have been introduced to account for detection and production asymmetries in order to extract the physical asymmetry $A_{\rm CP}$:

$$A_{\rm CP} = A_{\rm raw} - A_{\Delta}, \quad (2)$$

where A_{Δ} is the correction factor defined as:

$$A_{\Delta} = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)}), \quad (3)$$

where A_D is the instrumental asymmetry and A_P is the production asymmetry. The instrumental asymmetry A_D takes into account the effects induced by the different reconstruction and detection efficiencies and different cross sections in the interactions of oppositely charged particle with the detector material. The factors $\zeta_d = 1$ and $\zeta_s = -1$ follow the sign convention for f and f_s defined in Equation 1. The instrumental asymmetries are measured from data using a sample of tagged D^{*+} and untagged two-body D^0 decays. The production asymmetry has been estimated using a sample of $B^0 \to J/\psi K^{*0}$ decays assuming no CP violation. The factor $\kappa_{d(s)}$ takes into account the dilution due to neutral $B^0_{(s)}$ mixing. Since the B_s^0 has no valence quark in common with the incoming proton the production asymmetry is expected to be small. Assuming conservatively the same value as for B^0, the effect of $A_P(B_s^0)$ is negligible since κ_s is small due to the fast B_s^0 oscillations. Combining the instrumental and production asymmetries, the two correction factor $A_{\Delta}(B^0 \to K\pi) = (-0.7 \pm 0.6)\%$ and $A_{\Delta}(B_s^0 \to \pi K) = (1.0 \pm 0.2)\%$ have been obtained.

1.3. Systematic Uncertainties

The dominant systematics are linked to the PID calibration procedure, to the modeling of the signal and of the background in the fit procedure and to the instrumental and production asymmetries due to differences in the kinematic properties of B decays with respect to charm control samples, as well as different trigger and offline selections [4].

1.4. Results

Corrected for detection and production asymmetries, the following measurements have been obtained:

$$A_{\rm CP}(B^0 \to K\pi) = -0.088 \pm 0.011_{\rm stat} \pm 0.008_{\rm syst}$$

$$A_{\rm CP}(B_s^0 \to \pi K) = 0.27 \pm 0.08_{\rm stat} \pm 0.02_{\rm syst}.$$

The measurement of $A_{\rm CP}(B^0 \to K\pi)$ is in good agreement with the world average, $A_{\rm CP}^{PDG}(B^0 \to K\pi) = -0.097 \pm 0.012$ [5], and it constitutes the most precise measurement available to date. With a significance greater than 6σ, it is the first observation of CP violation in the B meson sector at a hadron collider. The significance for $A_{\rm CP}(B_s^0 \to \pi K)$ of 3.3σ makes it the first evidence for CP violation in the decays of B_s^0 mesons. The measurement is in good agreement with the only available measurement [3].

2. CP violation in $B^{\pm} \to DK^{\pm}$

The $B^{\pm} \to DK^{\pm}$ decays allow a theoretically clean extraction of the weak phase γ since they proceed only through tree diagrams. The strategy is to exploit the interference between the $b \to u$ and $b \to c$ transitions. In fact since the amplitude for the $B^- \to D^0 K^-$ contribution is proportional to V_{cb} whilst the $B^- \to \bar{D}^0 K^-$ amplitude depends on V_{ub}, if the D final state is accessible for both D^0 and $\bar{D}^0$, the interference of these two processes is sensitive to γ and may exhibit direct CP violation. The D final state can be a CP eigenstates: K^+K^- and $\pi^+\pi^-$ (GLW) or the so called ADS modes $D \to \pi^- K^+$. The interesting observables are partial widths and CP asymmetries for a total of 13 observables. There are three ratios of partial widths

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) - \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) - \Gamma(B^+ \to [f]_D \pi^+)}, \quad (4)$$

where f represents KK, $\pi\pi$ and the favoured $K\pi$ mode, six CP asymmetries:

$$A^f_h = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}, \quad (5)$$

where h can be a K or a π, and four charge-separated partial widths of the suppressed mode relative to the favoured:

$$R^{\pm}_h = \frac{\Gamma(B^{\pm} \to [\pi^{\pm} K^{\mp}]_D h^{\pm})}{\Gamma(B^{\pm} \to [K^{\pm}\pi^{\mp}]_D h^{\pm})}. \quad (6)$$

The measurements of the $B^{\pm}$ decays in the CP modes $[K^+K^-]_D h^{\pm}$ and $[\pi^{\pm}\pi^{\mp}]_D h^{\pm}$, the suppressed ADS mode $[\pi^{\pm}K^{\mp}]_D h^{\pm}$ and the favoured mode $[K^{\pm}\pi^{\mp}]_D h^{\pm}$ where h can be a pion or a kaon are presented using $1.0\,{\rm fb}^{-1}$ of data collected by LHCb [6].

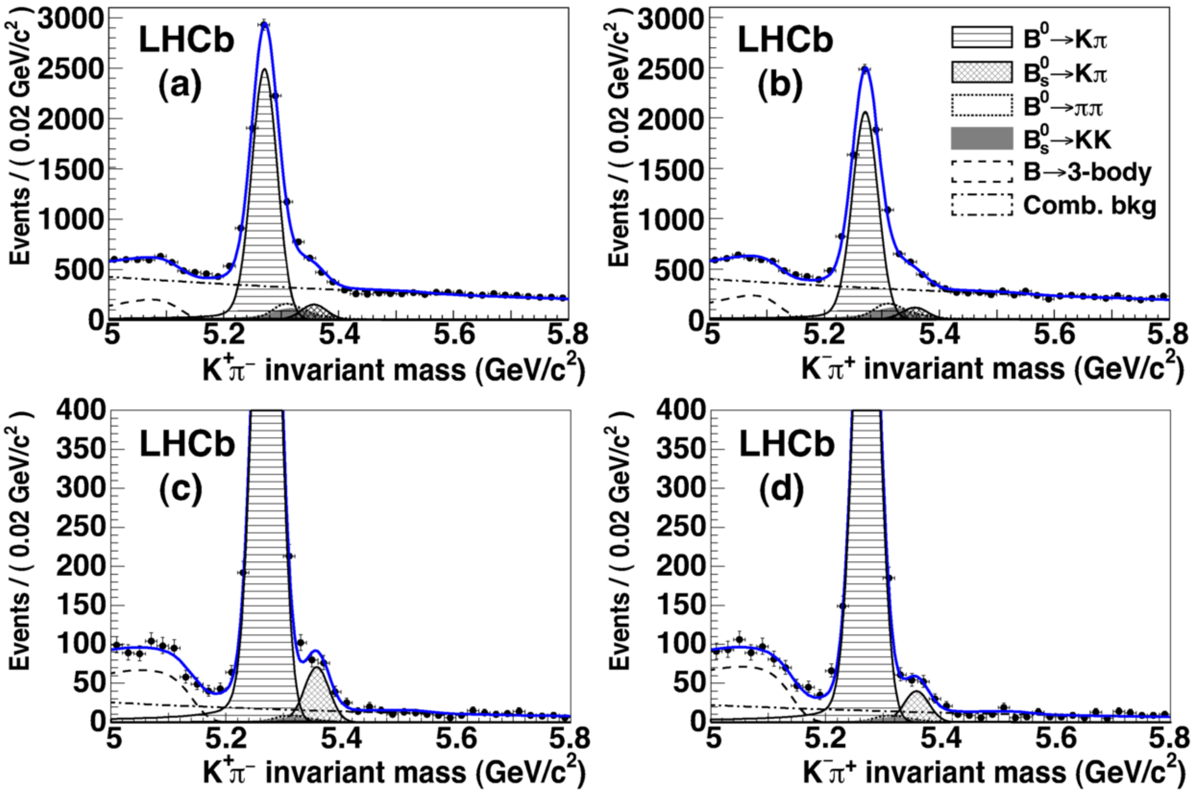

Figure 1: Invariant $K\pi$ mass spectra obtained using the selection adopted for $A_{\rm CP}(B^0 \to K\pi)$ (top) and for $A_{\rm CP}(B_s^0 \to K\pi)$ (bottom). The points with the error bars are the data and the solid line is the total fit. The main components contributing to the fit model are also shown.

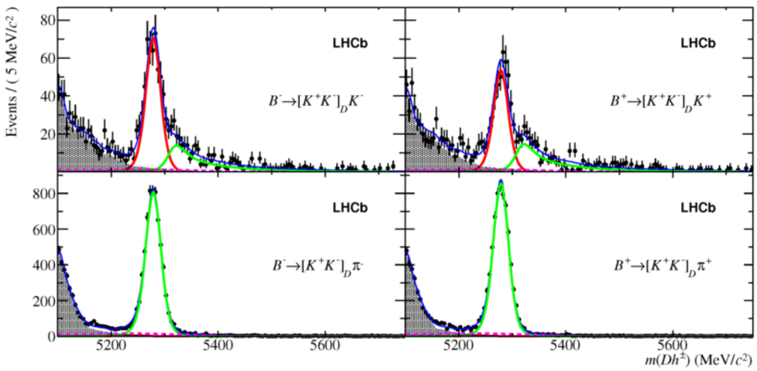

Figure 2: Invariant mass distributions of the CP eigenstate $B^\pm \to [KK]_D h^\pm$.

2.1. Selection Procedure

Every mass hypothesis combination $B \to [hh]_D h$ where $h = \pi, K$ is reconstructed. The ratios and asymmetries are extracted using a simultaneous fit of 16 slices: 2 (charges) $\times$ 4 (D modes) $\times$ 2 ($DK/D\pi$) (see Figures 2 and 3). The selection is based on a multivariate analysis in order to suppress the combinatorial background while charmless background is reduced by requiring a large flight distance of the D candidate from the B vertex.

2.2. Results

The results of the simultaneous fits with their statistical and systematic uncertainties are:

$$R^{K\pi}_{K/\pi} \quad = \quad 0.0774 \pm 0.0012 \pm 0.0018$$

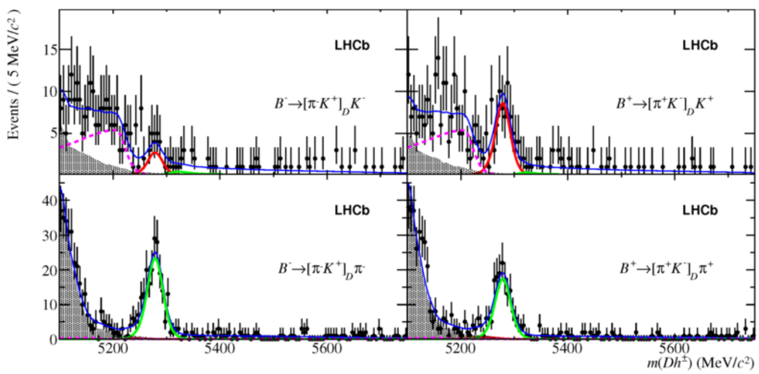

Figure 3: Invariant mass distribution of selected $B^\pm \to [\pi^\pm K^\mp]_D h^\pm$ candidates .

$$
\begin{aligned}
R^{KK}_{K/\pi} &= 0.0773 \pm 0.0030 \pm 0.0018\\
R^{\pi\pi}_{K/\pi} &= 0.0803 \pm 0.0056 \pm 0.0017\\
A^{K\pi}_{\pi} &= -0.0001 \pm 0.0036 \pm 0.0095\\
A^{K\pi}_{K} &= 0.0044 \pm 0.0144 \pm 0.0174\\
A^{KK}_{K} &= 0.0148 \pm 0.037 \pm 0.010\\
A^{\pi\pi}_{K} &= 0.0135 \pm 0.066 \pm 0.010\\
A^{KK}_{\pi} &= -0.020 \pm 0.009 \pm 0.012\\
A^{\pi\pi}_{\pi} &= -0.001 \pm 0.017 \pm 0.010\\
R^{-}_{K} &= 0.0073 \pm 0.0023 \pm 0.0004\\
R^{+}_{K} &= 0.0232 \pm 0.0034 \pm 0.0007\\
R^{-}_{\pi} &= 0.00469 \pm 0.00038 \pm 0.00008\\
R^{+}_{\pi} &= 0.00352 \pm 0.00033 \pm 0.00007
\end{aligned}
$$

Combining all these measurements we obtain:

$$
\begin{aligned}
R_{\mathrm{CP+}} &\sim\ < R^{KK}_{K/\pi}, R^{\pi\pi}_{K/\pi} > / R^{K\pi}_{K/\pi}\\
&= 1.007 \pm 0.038 \pm 0.012\\
A_{\mathrm{CP+}} &=\ < A^{KK}_{K}, A^{\pi\pi}_{K} >\\
&= 0.145 \pm 0.032 \pm 0.010\\
R_{\mathrm{ADS(K)}} &= 0.0152 \pm 0.0020 \pm 0.0004\\
A_{\mathrm{ADS(K)}} &= -0.52 \pm 0.15 \pm 0.02\\
R_{\mathrm{ADS}(\pi)} &= 0.00410 \pm 0.00025 \pm 0.00005\\
A_{\mathrm{ADS}(\pi)} &= 0.143 \pm 0.062 \pm 0.011.
\end{aligned}
$$

Both KK and $\pi\pi$ modes show positive asymmetries. Combining the two modes the statistical significance of the combined asymmetry is 4.5σ. The $B^\pm \to DK^\pm$ ADS mode is observed with $\sim 10\sigma$ statistical significance and it shows a large negative asymmetry (4.0σ). The $B^\pm \to D\pi^\pm$ ADS mode shows a hint of positive asymmetry (2.4σ). Combining all the $B^+ \to DK^+$ modes a total significance of 5.8σ of direct CP violation is observed.

3. Charmless three-body decays

Charmless three-body charged decays give the possibility to study the weak phase in interference patterns between two-body resonances in the Dalitz plot. The measurement of the integrated charge asymmetry as well as the asymmetry distributions in the Dalitz plot for $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays, performed at LHCb using a sample of data corresponding to $1.0\,\mathrm{fb}^{-1}$ are presented [7]. Both BaBar [8] and Belle [9] have observed the $B^+ \to K^+\pi^+\pi^-$ decay mode and BaBar has claimed evidence of CP violation in the $B^+ \to \rho^0 K^+$ with $\rho^0 \to \pi^+\pi^-$. The world average value for $B^+ \to K^+\pi^+\pi^-$ asymmetry is $A_{\mathrm{CP}}(B^+ \to K^+\pi^+\pi^-) = 0.038 \pm 0.028$ [5]. Concerning the $B^+ \to K^+K^+K^-$, the current asymmetry value is $A_{\mathrm{CP}}(B^+ \to K^+K^+K^-) = -0.017 \pm 0.030$ [5]. BaBar has claimed evidence of CP violation in the final state $B^+ \to \phi(1020)K^+$ with $\phi(1020) \to K^+K^-$ through an amplitude analysis [10].

3.1. Selection Procedure

Charmless three-body candidates are required to pass a hardware trigger that selects hadrons with high transverse energy in the calorimeters. The subsequent software trigger selects two-, three- or four-track secondary vertex with high transverse momenta and significant displacement from the primary vertex.

A common offline selection for all the charmless three-body decays has been developed thanks to the similar topology. The selection criteria can be found in [7]. The signal yields are determined from unbinned extended maximum likelihood fits (see Figure 4).

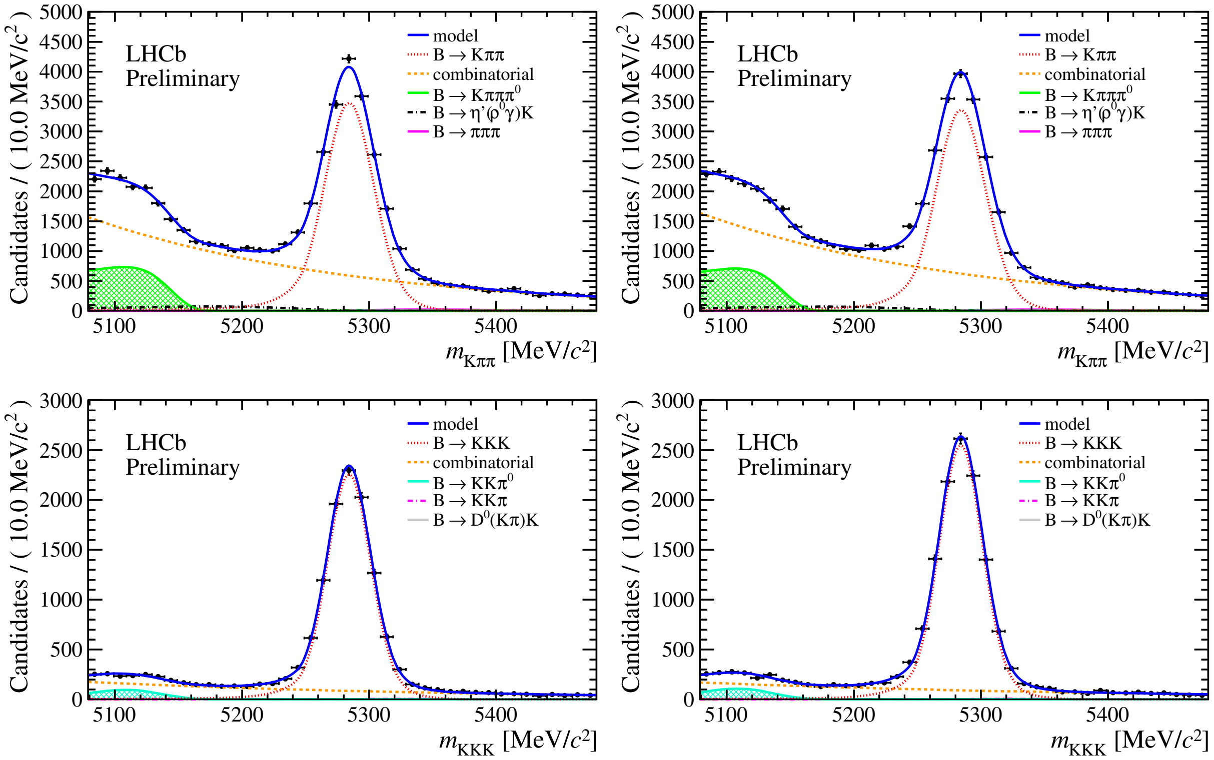

Figure 4: Invariant mass distributions of $B^+ \to K^+\pi^+\pi^-$ (top) and $B^\pm \to K^\pm K^+K^-$ (bottom) for B^+ (right) and B^- (left).

3.2. Results

In order to extract the charge asymmetry, the observed raw data asymmetries have to be corrected for the effects of production and detection asymmetries. The combined effects of production and detection asymmetries have been estimated from the raw asymmetry of $B^+ \to J/\psi K^+$ channel corrected by its CP asymmetry measured elsewhere [5]:

$$A_{\rm CP}(K^+h^+h^-) = \qquad (7)$$
$$= A^{RAW}_{\rm CP}(K^+h^+h^-) - A^{RAW}_{\rm CP}(J/\psi K^+) + A_{\rm CP}(J/\psi K^+).$$

The asymmetry for $B^+ \to K^+\pi^+\pi^-$ is:

$$A_{\rm CP}(B^+ \to K^+\pi^+\pi^-) =$$
$$= +0.034 \pm 0.009_{\rm stat} \pm 0.004_{\rm syst} \pm 0.007_{J/\psi K}.$$

The inclusive measurement has 2.8σ significance.

The $B^+ \to K^+K^+K^-$ asymmetry value is:

$$A_{\rm CP}(B^+ \to K^+K^+K^-) =$$
$$= -0.046 \pm 0.009_{\rm stat} \pm 0.005_{\rm syst} \pm 0.007_{J/\psi K}.$$

and with a significance of 3.7σ is the first evidence of inclusive CP asymmetry in charmless charged three-body B decays.

3.3. CP asymmetry in phase space

Raw asymmetries in bins of the two-body invariant mass projections have been extracted. The signal yield in each bin has been estimated from a simplified invariant mass fit due to the limited statistics. For the $B^+ \to K^+K^+K^-$ decay channel, the projections using low and high two-kaon invariant mass defined as $m^2_{K^+K^-low} < m^2_{K^+K^-high}$ are reported in Figure 5. There is no clear asymmetry around $\phi(1020)$ neither around $f_2(1525)$, but large asymmetries are measured in between these two resonances.

For the $B^+ \to K^+\pi^+\pi^-$ decay channel the raw asymmetry projections using two-body invariant mass $m^2_{\pi^+\pi^-}$ and $m^2_{K^\pm\pi^\mp}$ are reported in Figure 6. The $m^2_{\pi^+\pi^-}$ projection shows a clear asymmetry around $\rho(770)$ (see Figure 6).

4. Conclusions

2011 has been an excellent year for LHCb with several world-leading results for the search of CP violation in B hadron decays. In 2012 LHCb has already collected more than 1.5 fb^{-1}. Using the 2012 available statistics,

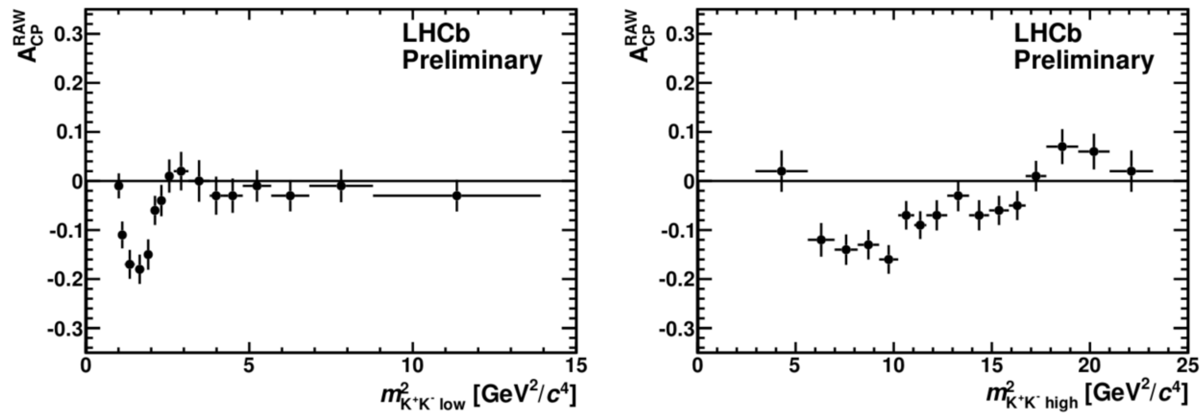

Figure 5: Raw asymmetry projections using $m^2_{K^+K^- low}$ and $m^2_{K^+K^- high}$ for $B^+ \to K^+K^+K^-$ decay channel.

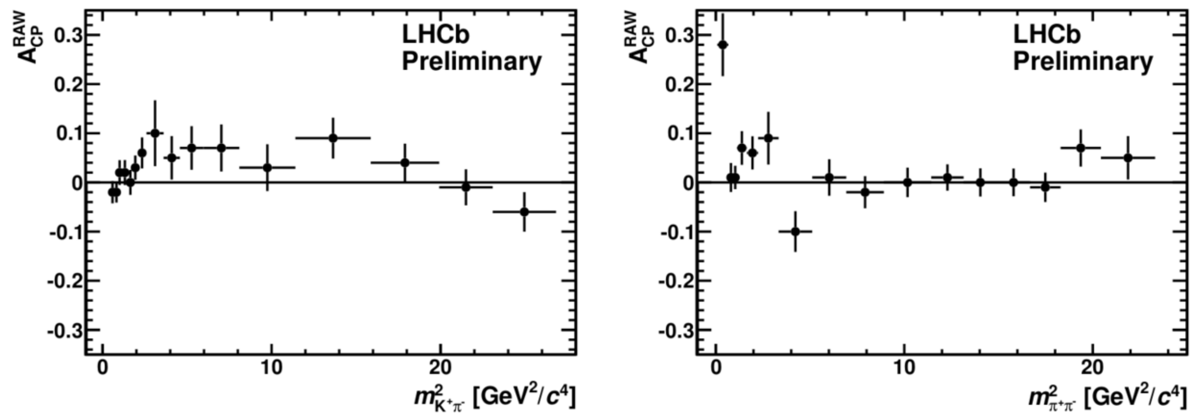

Figure 6: Raw asymmetry projections using $m^2_{\pi^+\pi^-}$ and $m^2_{K^\pm\pi^\mp}$ for $B^+ \to K^+\pi^+\pi^-$ decay channel.

LHCb will be able to continue to provide more competitive measurements, also in other channels that are currently under study.

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